

**FINAL
EVALUATION OF REMEDIATION TECHNOLOGIES
FOR DEMOLITION AREA 1**

**FOR THE
CAMP EDWARDS IMPACT AREA
GROUNDWATER QUALITY STUDY**

**MASSACHUSETTS MILITARY RESERVATION
CAPE COD, MASSACHUSETTS**

Prepared for

**NATIONAL GUARD BUREAU
ARLINGTON, VIRGINIA**

Prepared by

**OGDEN ENVIRONMENTAL AND ENERGY SERVICES
239 Littleton Road, Suite 1B
Westford, Massachusetts 01886**

Jonathan Bourne Public Library
10 Sandwich Rd.
Bourne, MA 02832

DISCLAIMER:

This document has been prepared pursuant to a government administrative order (US EPA Region 1 SDWA Docket No. 1-97-1019) and is subject to approval by the US Environmental Protection Agency. The opinions, findings, and conclusions expressed are those of the authors and not necessarily of the US Environmental Protection Agency.

Final Evaluation of Remedies for Demo 1

TABLE OF CONTENTS

1.0	INTRODUCTION.....	1
1.1	INITIAL TECHNOLOGY SCREENING.....	2
2.0	GROUNDWATER REMEDIAL TECHNOLOGIES.....	5
2.1	NO-ACTION.....	5
2.2	HYDRAULIC CONTAINMENT.....	5
2.2.1	Hydraulic Containment with Carbon Treatment.....	11
2.2.2	Hydraulic Containment with Aqueous-Phase Bioreactor Treatment.....	12
2.2.3	Hydraulic Containment with Zero-valent Iron or Pallidized Iron.....	12
2.2.4	Hydraulic Containment with Catalytic Oxidation.....	13
2.2.5	Hydraulic Containment with Ultraviolet Oxidation.....	13
2.3	IN-SITU TREATMENT.....	14
2.3.1	Impermeable Barrier Wall.....	14
2.3.2	Reactive Barrier Wall.....	14
2.3.3	In-Situ Recirculation Well.....	14
2.3.4	In-Situ Chemical Oxidation.....	15
2.3.5	Monitored Natural Attenuation.....	15
3.0	SOIL REMEDIAL TECHNOLOGIES.....	16
3.1	NO-ACTION.....	16
3.2	EXCAVATION AND DISPOSAL OR TREATMENT.....	16
3.2.1	Excavation and Landfill Disposal.....	23
3.2.2	Excavation and Treatment with Composting.....	23
3.2.3	Excavation and Biotreatment.....	25
3.2.4	Excavation and Treatment with White Rot Fungus.....	25
3.2.5	Excavation and Treatment with Incineration.....	25
3.2.6	Excavation and Treatment with Low Temperature Thermal Desorption.....	26
3.3	IN SITU TREATMENT.....	26
3.3.1	Landfarming.....	26
3.3.2	In-Situ Vitrification.....	26
3.3.3	Thermal Blanket.....	26
3.3.4	Electrokinetics.....	27
3.3.5	Deep Soil Mixing.....	27
3.3.6	Jet Grouting.....	27
3.3.7	Soil Flushing.....	28
3.3.8	Phytoremediation.....	28
3.3.9	Capping.....	28
4.0	CONCLUSIONS.....	29
5.0	RECOMMENDATIONS.....	29
6.0	REFERENCES.....	29

Tables

Table 1.	Regulatory criteria for groundwater and soil.....	1
Table 2a.	Comparison of Groundwater Ex-Situ Remedial Technologies.....	6
Table 2b.	Comparison of Groundwater In-Situ Remedial Technologies.....	8
Table 3a.	Comparison of Ex-Situ Soil Remedial Technologies.....	17

Final Evaluation of Remedies for Demo 1

Table 3b. Comparison of In-Situ Soil Remedial Technologies.	19
--	----

Figures

Figure 1. Distribution of explosive compounds in soil at Demolition Area 1.	3
Figure 2. Distribution of explosive compounds in groundwater at Demolition Area 1.	4
Figure 3. Cost comparison of various groundwater remedial technologies identified for Demolition Area 1 at MMR.	10
Figure 4. Cost comparison of various soil remedial technologies identified for Demolition Area 1 at MMR.	24
APPENDIX A: Estimated Pumping Rates and Drawdown.....	34
APPENDIX B: Responses to EPA Comments dated 11/8/99 and 1/13/00 on the Draft Evaluation of Remediation Technologies for Demolition Area 1	37

Final Evaluation of Remedies for Demo 1

1.0 INTRODUCTION

Remedial technologies were evaluated for explosive contaminants present at Demolition Area 1 of the Massachusetts Military Reservation (MMR). Identification of remedial technologies was based on the nature and distribution of the contamination present at the Demolition Area 1 site. The principal contaminants of concern (COCs) for soil at the Demolition Area 1 site are 2,4-dinitrotoluene (2,4-DNT), 2,6-dinitrotoluene (2,6-DNT), 2-amino-4,6-dinitrotoluene (2A-DNT), 4-amino-2,6-dinitrotoluene (4A-DNT), octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX), hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), and 2,4,6-trinitrotoluene (TNT) based on the Phase I results (Ogden, 1998). The fate-and-transport properties of the COCs are discussed in Ogden (1997 and 1998). Groundwater contamination at Demolition Area 1 appears limited to a 20 acre area with soil contamination confined to the Demolition 1 area, approximately one to five acres, based upon results from the Completion of Work Report for Phase I and monitoring wells installed as part of a response plan to Demolition Area 1.

The focus of this report was on individual technologies, however it should be recognized that many of the possible technologies could be combined to reduce cost or increase overall effectiveness. To evaluate combinations of technologies would require a more detailed, cost and performance analysis, similar to what would be done under a Feasibility Study under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) process.

The regulatory criteria used for the evaluation (see Table 1), applicable or relevant and appropriate requirements (ARARs), were EPA Health Advisories, EPA Maximum Contaminant

Table 1. Regulatory criteria for groundwater and soil.

Chemical	Groundwater (ug/L)					Soil (mg/kg)
	EPA MCL ¹	EPA Lifetime HA ¹	EPA 10 ⁻⁴ Cancer Risk ¹	10 ⁻⁶ Cancer Risk	MADEP MCP Method 1 Groundwater Standards GW-1	MADEP MCP Method 1 Soil Standards
2A-DNT	-	-	-		-	-
4A-DNT	-	-	-		-	-
2,4-DNT	-	-	5	0.05	30	0.7
2,6-DNT	-	-	5	0.05	-	-
HMX	-	400	-		-	-
RDX	-	2	30	0.3	-	-
TNT	-	2	100	1	-	-

- no criteria available

Levels, Method 1 GW-1 Groundwater Standards, Method 1 Risk-Based Soil Cleanup Levels for Massachusetts Department of Environmental Protection (MADEP) under the Massachusetts Contingency Plan (MCP). The Method 1 Soil Standard is a conservative risk-based concentration protective of groundwater or a receptor coming in contact with soil. The MADEP MCP Method 1 GW-1 standard is a risk-based number protective of groundwater. The EPA Health Advisory

¹ USEPA Office of Water, EPA 822-B-96-002, October 1996

Final Evaluation of Remedies for Demo 1

used for groundwater was the lifetime risk for a 70-kg adult or if not available the 10^{-4} cancer risk. Typically, soil risk numbers are developed using a model to assess what level of soil contamination is protective of groundwater. This type of analysis has not been done for MMR, but will be performed after the results of deep soil sampling at Demolition Area 1 are available. The soil results for the Demolition Area indicate six explosive compounds have been detected (Figure 1)². The explosive concentrations in soil range from 0.12 to 9.3 mg/kg. One sample with 2,4-DNT (S19DAD) exceed the Method 1 GW-1 Groundwater Standard. The groundwater results indicate the presence of 2,4-DNT, 2A-DNT, 4A-DNT, TNT, HMX, and RDX explosive compounds (Figure 2)². The concentrations range from non-detect to 370 ug/L. RDX and TNT exceed the EPA HA lifetime screening guidance.

1.1 Initial Technology Screening

Potential technologies for soil and groundwater sampling were evaluated for inclusion in this report. Each technology was evaluated according to three criteria: implementability, effectiveness, and cost. The U.S. Environmental Protection Agency (EPA) describes these screening criteria as follows (see 40 CFR 300.430 (e)(7):

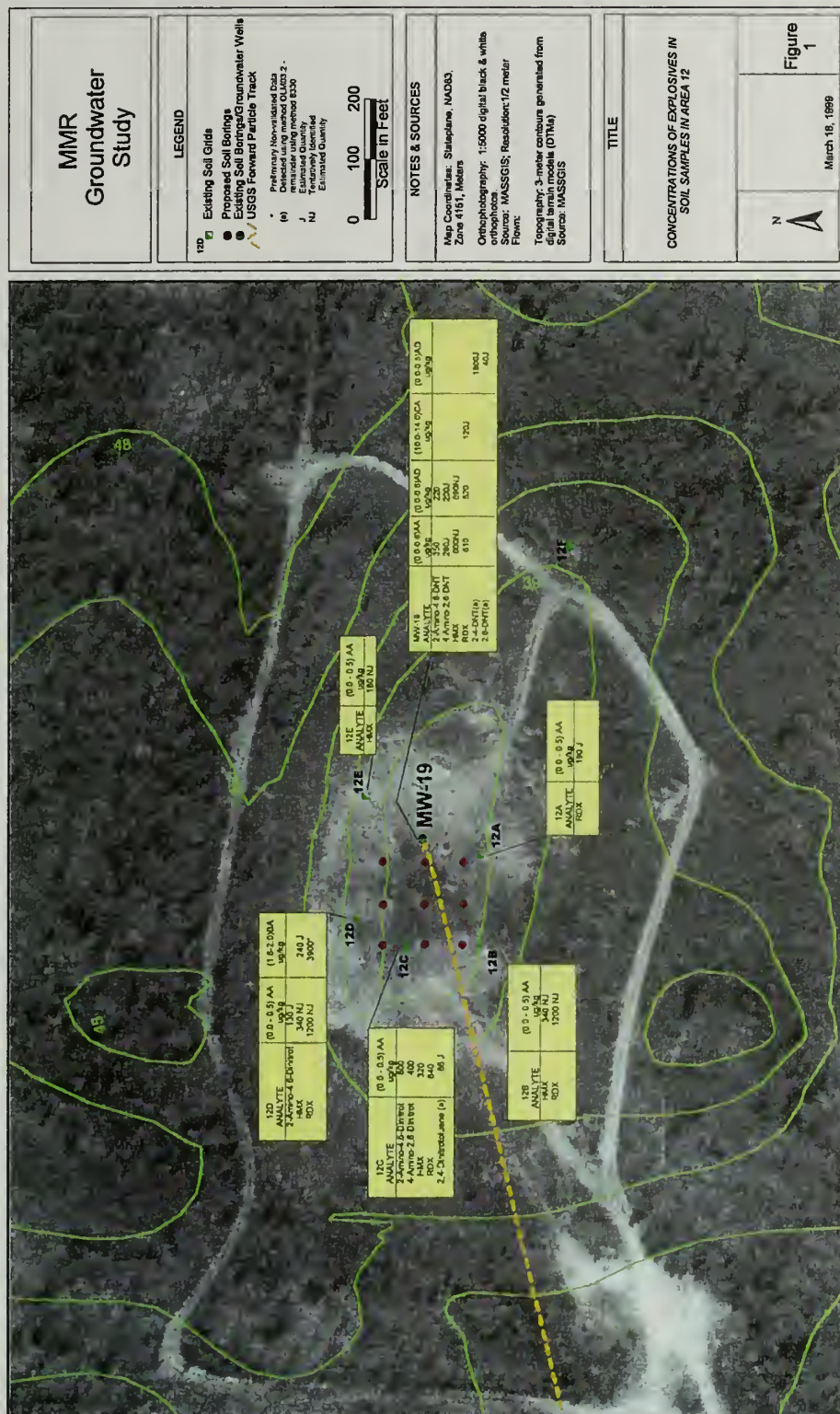
- Effectiveness consists of the degree to which toxicity, mobility and volume are reduced and addresses three elements which include the: 1) potential to restore the site to remediation goals, 2) potential impacts to human health and the environment during remediation, and 3) reliability and proven effectiveness of the technology for the contaminants present at the site.
- Implementability addresses the technical and administrative feasibility and availability of constructing, operating, and maintaining the technology. This step is considered in order to rule out ineffective technologies given the site conditions.
- Cost is evaluated on a relative basis for both construction and long term operation and maintenance and plays a limited role in the evaluation of the technologies. The cost analysis is made on the basis of an engineering judgment and whether the cost is low, medium, or high.

The approach used in the pre-screening process of evaluating the applicable technologies for explosive remediation was to first consider all technologies available, including innovative technologies. The next step was then to determine which technologies would be applicable for remediation of explosive compounds. During this stage a large number of technology categories were determined not suitable for explosives remediation, such as thermal, vapor, surfactant, and co-solvent methods for groundwater and vapor technologies for soil. Specific examples of the vapor phase technologies not suitable for explosives remediation include; Bioventing, Bioslurping, Dynamic Underground Stripping (DUS), and UVB systems for groundwater and soil vapor extraction (SVE), Six-Phase Heating, and Steam Stripping for soil.

² Additional results of soil and groundwater sampling have become available since this draft report was published in May 1999. These results, along with the results of other investigations currently underway, will be considered in the Technology Screening Report to be prepared for Demo 1 in accordance with EPA Administrative Order SDWA-1-2000-0014. Therefore, the data in Figures 1 and 2 are circa May 1999.

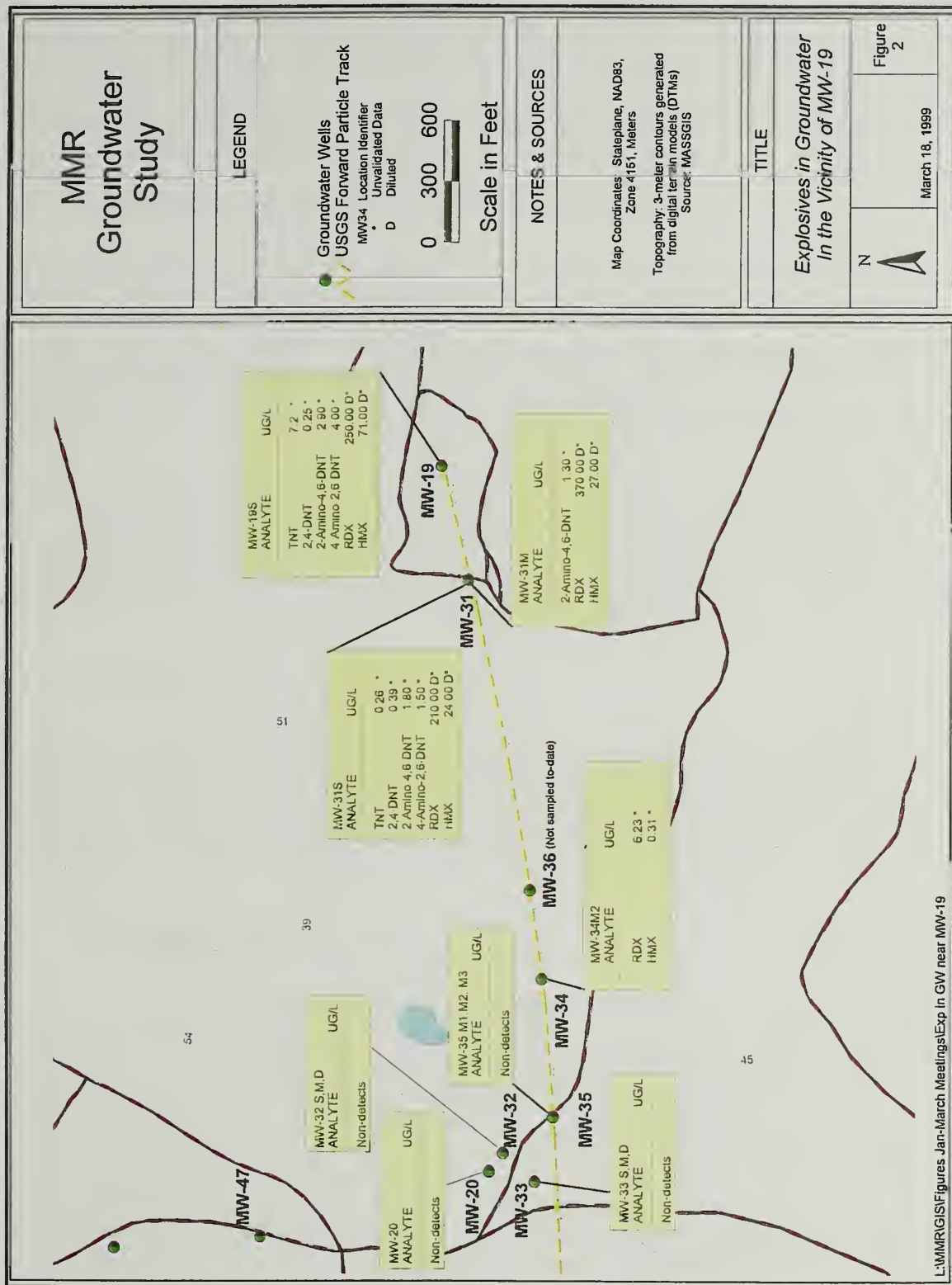
Final Evaluation of Remedies for Demo 1

Figure 1. Distribution of explosive compounds in soil at Demolition Area 1.



Final Evaluation of Remedies for Demo 1

Figure 2. Distribution of explosive compounds in groundwater at Demolition Area 1.



Final Evaluation of Remedies for Demo 1

The technologies which passed the initial screening process for groundwater are No-Action, Pump-and-Treat, Barrier Walls, In-Situ Recirculation, Chemical Oxidation, and Natural Attenuation. The technologies which passed the initial screening process for soil are No-Action, Excavation, Composting, Landfarming, Capping, Phytoremediation, Soil Flushing, Jet Grouting, Soil Mixing, Electrokinetics, Thermal Blanket, and In-Situ Vitrification. Each technology that passed the initial screening is discussed in detail in Sections 2 (for groundwater) and 3 (for soil). Additional technologies were considered as part of the initial screening but are not included in this discussion since they were not applicable to explosives remediation.

2.0 GROUNDWATER REMEDIAL TECHNOLOGIES

A comparison of the ex-situ and in-situ groundwater remedial technologies that were selected in Section 1.1 based on effectiveness, implementability, and cost is presented in Tables 2a and 2b. These technologies are then evaluated using seven criteria; 1) overall protection of human health and the environment, 2) compliance with ARARs, 3) long-term effectiveness and performance, 4) reduction of toxicity, mobility, or volume through treatment, 5) short-term effectiveness, 6) implementability, and 7) cost. Each groundwater remedial technology is discussed in detail in Section 2.

The COCs at the Demolition Area 1 site in groundwater are HMX, RDX, TNT, 2,4-DNT, 2A-DNT, and 4A-DNT. These COCs were selected based on the 1997-1999 groundwater results for Demo Area 1 showing exceedances of drinking water criteria for explosives. If the continuing investigations of Demo Area 1 identify other analytes that exceed drinking water criteria, an evaluation of remedies may need to be developed to address these other analytes.

2.1 No-Action

Under this alternative, the Demolition Area 1 would be allowed to continue in its present condition without any efforts to control the migration of explosives in groundwater. This alternative provides a basis for assessing the effects of taking remedial action, and provides an environmental baseline against which other alternatives are compared. Figure 3 presents a comparison of the relative cost of each groundwater treatment technology.

2.2 Hydraulic Containment

In a hydraulic containment system groundwater is pumped to the surface from one or more wells, treated, and discharged (i.e. to surface water or reinjected into the aquifer). Single or multiple wells can be used, with a higher efficiency possible with multiple extraction wells, i.e. lower pump rates for the same capture zone width. Various methods are used to treat the water, depending on the contaminant and discharge limit. Pump-and-treat has been viewed with growing disfavor for the remediation of contaminated groundwater due to its inability to achieve remedial goals and its high operational and maintenance cost (NRC, 1994 and EPA, 1992). A growing trend is the use of pump-and-treat as a hydraulic containment tool to isolate a source area (Nyer et al. 1996). In this context, the manner in which pump-and-treat is considered for the Demolition Area 1 site is as a hydraulic containment system. The system could utilize vertical or

Final Evaluation of Remedies for Demo 1

Table 2a. Comparison of Groundwater Ex-Situ Remedial Technologies.

Criteria	Ex-Situ Remedial Technologies		
	No-Action	Hydraulic Containment with Carbon Treatment	Hydraulic Containment with BioReactor Treatment
Overall Protection of Human Health and the Environment	Not protective of human health and the environment	Protective of human health and the environment.	Protective of human health and the environment.
Compliance with ARARs	Implementation of this alternative does not satisfy ARAR's.	Would comply with ARAR's.	Would comply with ARAR's.
Long-term Effectiveness and Performance	Unacceptable level of risk would remain if this alternative would be implemented.	An acceptable level of risk would remain.	An acceptable level of risk would remain.
Reduction of Toxicity, Mobility, or Volume through Treatment	Implementation of this alternative will not reduce toxicity, mobility, and volume of residual contamination.	Reduction of toxicity, mobility, and volume through on-site treatment to remove explosives from groundwater.	Reduction of toxicity, mobility, and volume through on-site treatment to remove explosives from groundwater.
Short-term Effectiveness	No increased risk to the surrounding community or the environment.	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.
Implementability	Not applicable.	Materials and services available.	Materials and services available.
Cost	Not applicable.	High.	High.
Recommendation	Not applicable to site since risk is not reduced.	Recommended as a viable treatment option.	Recommended as a viable treatment option.

Final Evaluation of Remedies for Demo 1

Table 2a. Comparison of Groundwater Ex-Situ Remedial Technologies.

Criteria	Ex-Situ Remedial Technologies		
	Hydraulic Containment with Zero-Valent Iron Treatment	Hydraulic Containment with Catalytic Oxidation Treatment	Hydraulic Containment with Ultraviolet Oxidation Treatment
Overall Protection of Human Health and the Environment	Protective of human health and the environment.	Protective of human health and the environment.	Protective of human health and the environment.
Compliance with ARARs	Would comply with ARAR's.	Would comply with ARAR's.	Would comply with ARAR's.
Long-term Effectiveness and Performance	An acceptable level of risk would remain.	An acceptable level of risk would remain.	An acceptable level of risk would remain.
Reduction of Toxicity, Mobility, or Volume through Treatment	Reduction of toxicity, mobility, and volume through on-site treatment to remove explosives from groundwater.	Reduction of toxicity, mobility, and volume through on-site treatment to remove explosives from groundwater.	Reduction of toxicity, mobility, and volume through on-site treatment to remove explosives from groundwater.
Short-term Effectiveness	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.
Implementability	Materials and services available.	Materials and services available.	Materials and services available.
Cost	High.	High.	High.
Recommendation	Recommended as a viable treatment option.	Recommended as a viable treatment option.	Recommended as a viable treatment option.

Final Evaluation of Remedies for Demo 1

Table 2b. Comparison of Groundwater In-Situ Remedial Technologies.

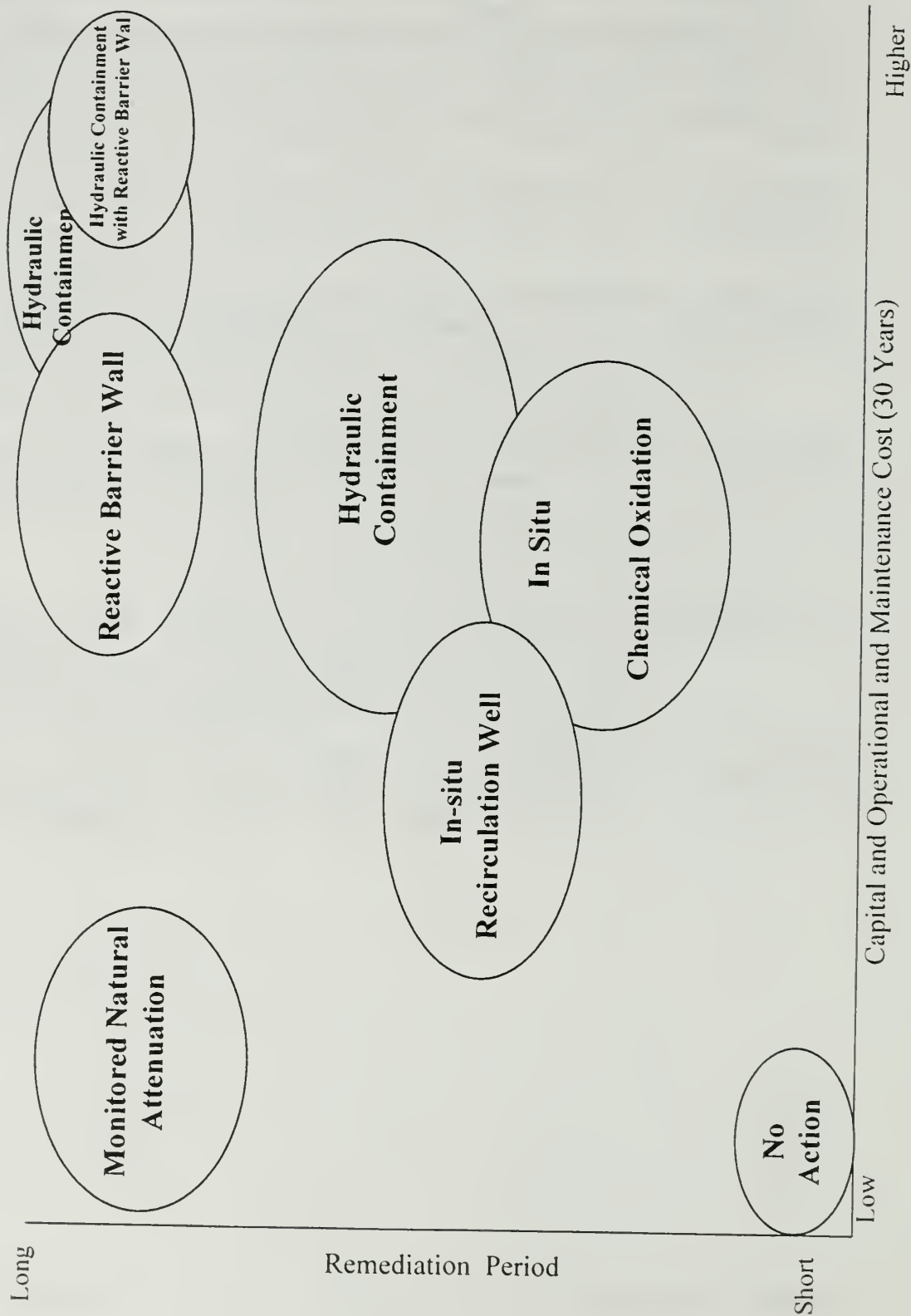
Criteria	In-Situ Remedial Technologies		
	No-Action	Reactive Barrier Walls	Impermeable Barrier Walls
Overall Protection of Human Health and the Environment	Not protective of human health and the environment	Protective of human health and the environment.	Protective of human health and the environment.
Compliance with ARARs	Implementation of this alternative does not satisfy ARAR's.	Would comply with ARAR's.	Would comply with ARAR's.
Long-term Effectiveness and Performance	Unacceptable level of risk would remain if this alternative would be implemented.	An acceptable level of risk would remain.	An acceptable level of risk would remain.
Reduction of Toxicity, Mobility, or Volume through Treatment	Implementation of this alternative will not reduce toxicity, mobility, and volume of residual contamination.	Reduction of toxicity, mobility, and volume through on-site treatment to remove explosives from groundwater.	Reduction of toxicity, mobility, and volume through on-site treatment to remove explosives from groundwater.
Short-term Effectiveness	No increased risk to the surrounding community or the environment.	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.
Implementability	Not applicable.	Materials and services available.	Materials and services available.
Cost	Not applicable.	High	High
Recommendation	Not applicable to site since risk is not reduced.	Recommended as a viable treatment option.	Recommended as a viable treatment option.

Final Evaluation of Remedies for Demo 1

Table 2b. Comparison of Groundwater In-Situ Remedial Technologies (continued).

Criteria	In-Situ Remedial Technologies		
	In-Situ Recirculation Well	Chemical Oxidation	Monitored Natural Attenuation
Overall Protection of Human Health and the Environment	Protective of human health and the environment.	Protective of human health and the environment.	Not protective of human health and the environment
Compliance with ARARs	Would comply with ARAR's.	Would comply with ARAR's.	Implementation of this alternative does not satisfy ARAR's.
Long-term Effectiveness and Performance	An acceptable level of risk would remain.	An acceptable level of risk would remain.	An unacceptable level of risk would remain if this alternative would be implemented.
Reduction of Toxicity, Mobility, or Volume through Treatment	Reduction of toxicity, mobility, and volume through on-site treatment to remove explosives from groundwater.	Reduction of toxicity, mobility, and volume through on-site treatment to remove explosives from groundwater.	Implementation of this alternative will not reduce toxicity, mobility, and volume of residual contamination.
Short-term Effectiveness	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.	No increased risk to the surrounding community or the environment.
Implementability	Innovative technology could be implemented. Materials and services not commercially available.	Innovative technology could be implemented. Materials and services available but limited.	Innovative technology could be implemented. Materials and services available.
Cost	Medium to High	High	Low
Recommendation	Not recommended as a viable treatment option.	Possible treatment option.	Possible treatment option.

Figure 3. Cost comparison of various groundwater remedial technologies identified for Demolition Area 1 at MMR.



horizontal wells. The wells could be placed at the leading downgradient edge of the groundwater contamination area or through the center of the area of contamination. Other groundwater collection options could include the use of barrier walls or reinjection wells to funnel the area of groundwater contamination to a smaller area. This would be done to minimize the amount of water needed to be pumped from the aquifer and treated. Later the hydraulic containment system could be augmented or replaced with additional wells or some other remedial technology to perform hotspot remediation at the source. The use of subsurface drains such as a French Drain would not be practical at the Demo 1 site due to the depth to groundwater and the high groundwater flow velocities. Calculations were also performed in Appendix A to assess the likely capture zone size based on a single pumping well and the associated drawdown.

Treated water can also be reinjected into the aquifer to enhance gradient control, reinjected into the vadose zone, or applied to the ground surface to enhance the dissolution of explosives. Reinjection can be accomplished with a number of different techniques such as reinjection wells, infiltration galleries of wells, trench infiltration galleries, subsurface drains, or landsurface application. In this scenario the amount of water extracted to obtain a given capture zone width can be much less than stand-alone extraction wells since the reinjection wells can be used to push water to the extraction wells. The reinjection points could be laterally on either side of the area of contamination, at the extraction well location to minimize groundwater withdrawals, in the source area to enhance dissolution and flushing of contaminants through the vadose zone, or upgradient of the source area to increase the groundwater flow velocities in the aquifer. Groundwater flow modeling would be necessary to optimize the system to the best arrangement of extraction and reinjection wells. Although initial capital costs are higher than for extraction only system, due to the need for installation of an injection system and additional infrastructure, long term operational and maintenance treatment costs are lower due to the smaller volume of water pumped and treated.

2.2.1 Hydraulic Containment with Carbon Treatment

The pump-and-treat technology consists of passing the extracted groundwater through a treatment bed or reactor vessel containing granular activated carbon (GAC). The technology has been demonstrated for explosives (HMX, RDX, and TNT) at several sites, including the Pantex Plant in Amarillo, Texas, Milan Army Ammunition Plant (AAP) in Milan, Tennessee, and Badger AAP in Wisconsin (Fleming et al. 1996; Bricka and Fleming, 1995; and Hinshaw et al. 1987). Since these are the same as contaminants at MMR there would be no need for a pilot test or treatability study. Some limited testing and evaluation of chemical data would be necessary to evaluate the need for pretreatment of water to remove iron, manganese, and hardness to avoid fouling the GAC. If desired, the technology is readily implementable for full-scale remediation.

Recent studies conducted at the Cornhusker AAP evaluated the removal of RDX, trinitrobenzene (TNB), TNT, and HMX from water (Fleming et al. 1996). The tests included the evaluation of six GACs, two carbonaceous resins, one polymeric resin, and two organophilic clays. The polymeric resin and organophilic clays were not effective in reducing contaminant concentrations below the effluent limit of 2 ug/L. GAC was found to satisfactorily remove the explosives of interest with some differences in efficiency between the various types of GAC. Studies have also been conducted at the Milan AAP, Burlington Iowa AAP (Hinshaw et al. 1987), Radford AAP, Lone Star AAP, Kansas AAP, Joliet AAP, and Picatinny Arsenal (Bricka and Fleming, 1995). In all AAP cases, the initial concentrations of explosives in water exceeded 100 mg/L. These studies found GAC to perform satisfactorily for the removal of explosives.

One drawback to the GAC treatment technology is the creation of contaminated carbon, which becomes a solid hazardous waste. Management of the carbon as a hazardous waste is expensive. Regeneration of the carbon loaded with explosives using base hydrolysis has been evaluated and looks promising (Heilmann et al. 1996 and Knezovich et al. 1994). Direct treatment of wastewater with base hydrolysis, however is not economical (Heilmann et al. 1996). Other approaches are to wash the carbon using heated water and ethanol to remove the contaminants and then run the effluent through a microbiological consortium (Knezovich et al. 1994), regeneration using acetone (Fleming et al. 1996), and regeneration using thermal oxidation. Regenerated carbon costs are approximately \$55,000/year and virgin carbon approximately \$87,000/year for a 700 gpm system (Fleming et al. 1995). The system discussed by Fleming et al. (1995) was treating groundwater with explosive contaminant levels up to 3 orders of a magnitude higher than what has been observed at MMR. It is unclear what size treatment system would be needed at Demolition Area 1 since the extent of contamination is still under investigation. However, a 700 gpm system likely would be on the upper end of what is needed based on other narrow plumes at MMR and calculations made in Appendix A. This technology is widespread and most large-scale environmental engineering firms have experience with this technology. A treatability test would be necessary to further evaluate any GAC regeneration process before implementation at MMR.

2.2.2 Hydraulic Containment with Aqueous-Phase Bioreactor Treatment

The bioreactor treatment process consists of passing extracted groundwater through a reactor containing a microbiological consortium to degrade the contaminants. It has been well established in the literature that TNT is susceptible to biodegradation under both aerobic and anaerobic conditions and RDX and HMX are susceptible to biodegradation under anaerobic conditions in the soil column (Brannon et al. 1998; Brannon et al. 1997; Bruns-Nagel et al. 1996; Haigler and Spain, 1996; Bradley and Chapelle, 1995; Bradley et al. 1994; Unkefer et al. 1990; and Soli, 1973). Limits on the technology include the volume of water to be treated and the possibility of production of recalcitrant TNT degradation products such as the DNTs. Tyndall and Vass (1993) claim to have isolated a bacterium that results in complete destruction of TNT but the effectiveness of this bacterium has not been tested for RDX and HMX. Most pump-and-treat bioreactor applications have been limited to 10 gpm or less pumping rates. Most large-scale environmental engineering firms will have experience with this technology. Extensive bench and pilot scale work would be necessary prior to implementing this technology at MMR.

2.2.3 Hydraulic Containment with Zero-valent Iron or Pallidized Iron

The technology consists of passing the extracted groundwater through a reactor vessel containing zero-valent iron or pallidized iron. This is a promising potential treatment option based on the chemical structure of the explosives in groundwater at MMR. Limited laboratory work has been performed by Oak Ridge National Laboratory, U.S. Army Corps of Engineers, Waterways Experiment Station, and others (McGrath, 1998; Korte, 1998; Agrawal and Tratnyek, 1995; Agrawal et al. 1995; Agrawal and Tratnyek, 1994; and Schwarzenbach et al. 1994). Advantages are low operational and maintenance costs and no need for off-site disposal of media, unlike carbon. The reaction involves the destruction of the nitroaromatic compound so there is no buildup of contaminants on the reactive media. By-products released into water include, nitrate, aromatic amines, hydroxylamines, nitroso compounds, and hydrogen. One potential drawback is the creation of intermediate byproducts that may be as toxic as the starting compound, such as

hydroxylamines and nitroso compounds. Thus, iron treatment may need to be combined with a biological process, which can further reduce the aromatic amines, hydroxylamines, and nitroso compounds. Additional potential drawbacks include clogging of media over time or reduced treatment efficiency and need for regeneration of iron/palladium surface to remove salt precipitates, typically calcium or ferrous carbonates. EnviroMetal Technologies Inc. holds the license on the patent and is the commercial provider of the zero-valent iron system for volatile organic compounds and the Research Corporation for palladized iron covering all organic compounds. The patents do not appear to cover explosives. Extensive bench and pilot scale work would be necessary prior to implementing this technology at MMR.

2.2.4 Hydraulic Containment with Catalytic Oxidation

The technology consists of passing the extracted groundwater through a catalytic oxidation unit. This is a potential treatment option based on the chemical structure of the explosives in groundwater at MMR, but a treatability test would be required to prove its feasibility. However, catalytic oxidation units are more appropriate for higher contaminant concentrations than seen at MMR. Typically, a catalytic oxidation unit has a fairly high capital and long term operational and maintenance costs. Numerous commercial vendors are available for the catalytic oxidation units. Most large-scale environmental engineering firms have experience with this technology.

2.2.5 Hydraulic Containment with Ultraviolet Oxidation

The technology consists of passing the extracted groundwater through an ultraviolet photooxidation unit or oxidizing the water with ozone. Pilot-scale tests of this technology have been performed at the Kansas AAP, Crane AAP, Iowa AAP, Holston AAP, and Picatinny Arsenal (Fleming et al. 1995 and LeFaivre and Peyton, 1994). The study at Picatinny Arsenal found that RDX could be reduced below 1 ug/L from a starting concentration of 4.5 ug/L (Flemming et al. 1995). Ultraviolet oxidation with ozone was more efficient than ultraviolet oxidation alone. However, unknown and unidentifiable compounds were observed in the effluent stream. These studies found that ultraviolet oxidation could destroy TNT, RDX, HMX, and tetryl. However, TNB accumulates if an insufficient residence time is used. TNB is a degradation product of TNT. Studies of water from the Bangor U. S. Naval Submarine Site indicated ultraviolet photooxidation was cost competitive with other treatment technologies, although a number of recalcitrant TNT degradation products were observed in the effluent stream (LeFaivre and Peyton, 1994). Full-scale treatment systems can range up to 2,000 gpm.

Full-scale operational and treatment costs are estimated at \$55,000 to \$90,000/year with a unit cost of approximately \$700,000 (Fleming et al. 1995) for a 5 gpm system treating RDX at a concentration of less than 5 ug/L. Several commercial vendors market this technology: Ultrox Inc., Peroxidation Systems Inc., Solarchem Inc., Excalibur Enterprises Inc., Nutech Inc., and Purus Inc. It has been the author's and others within Ogden's experience that this technology has higher than anticipated operational and maintenance costs over the long term, due to equipment failure as result of fouling issues. Most large-scale environmental engineering firms have experience with this technology. Extensive bench and pilot scale work would be necessary prior to implementing this technology at MMR.

2.3 In-Situ Treatment

2.3.1 Impermeable Barrier Wall

The technology consists of installing an impermeable barrier such as sheet piling, clay, or cement slurries to change groundwater flow directions. The barriers could be installed upgradient of the source area to deflect groundwater around the contaminated source. A barrier wall installed downgradient of a source area is generally used to intercept and funnel a plume or cut off a source area. In this configuration the barrier wall is usually used in conjunction with an extraction well(s) or reactive barrier, i.e. "gate". The effect of the barrier wall is to funnel the water into a smaller region so less water is needed to be extracted and treated. Another concept is to complete a four-sided barrier around the source area using either an impermeable cap to restrict recharge via precipitation, or using a well in the center to maintain hydraulic control. Barrier walls can be constructed using cement-bentonite slurry, soil bentonite slurry, steel sheet piling, high-density polyethylene liner, or various polymer slurries. Given the site geology, the concept would have to be for a hanging barrier wall, possibly coupled with some hydraulic control, i.e. limited pumping since the uppermost confining unit is a till at 300+ ft below ground surface. A hanging barrier wall is so named since it is not keyed into a lower impermeable or confining geologic unit such as clay or bedrock. The depth to groundwater outside of the kettle hole at Demolition Area 1 would be approaching the limits of the technology in terms of installation. One drawback to barrier walls is the high capital cost associated with the installation of deep walls, another is proving that the barrier wall is working. Most large-scale environmental engineering firms have experience with this technology.

2.3.2 Reactive Barrier Wall

The technology consists of installing a permeable barrier to treat contaminants in-situ. Usually, the technology is coupled with an impermeable barrier wall and in this configuration is called a "funnel-and-gate". The treatment medium is usually zero-valent iron, as described in Section 2.2.3, but other materials are possible and are being evaluated such as biological consortia, bimetals, zeolites, peat, etc. As is the case with an impermeable barrier wall, there is a high capital cost associated with the installation of a deep reactive barrier wall. A significant unknown with reactive barrier walls is the performance over the long term of the reactive media. The oldest reactive barrier wall has been operational less than five years. Laboratory work has shown that clogging due to the formation of precipitates can potentially be a significant issue (Horney et al. 1995). The approach is fairly new and only a few environmental engineering firms have the expertise for this technology. Extensive bench and pilot scale work would be necessary prior to implementing this technology at MMR.

2.3.3 In-Situ Recirculation Well

The technology consists of two horizontal wells where water is extracted at one well and then reinjected at another. The horizontal wells can be placed one above the other or parallel to each other at the same depth. They can also be placed perpendicular to the groundwater flow direction to intercept a plume for containment or they can be placed down the axis of plume for reduction of mass. The advantage of such a system is that groundwater plumes are typically narrow in the vertical direction making a horizontal well better suited for the contaminant distribution and thus

Final Evaluation of Remedies for Demo 1

more efficient than a vertical well. A thin narrow contaminated region such as the one at Demolition Area 1 is ideally suited for this type of technology.

The concept was recently proven at a Department of Energy (DOE) site in Ohio using in-situ treatment canisters for treatment of a mixed waste plume (Korte et al. 1998). The treatment canisters were placed in the extraction well so all contaminants were treated below the ground surface. The system was engineered such that the treatment canisters were recoverable and the treatment media could be replaced or regenerated if necessary. Another in-situ recirculation well was installed at a DOE site in Florida. This system consisted of injection of microbes in one well and extraction at another well. The extracted water was inoculated and then reinjected to create a circulation cell. Both in-situ recirculation wells were successful in removing contaminant mass.

The primary disadvantage of this technology is that it has not been demonstrated effective for explosives. It is possible that the demonstrated recirculation technologies could be modified to incorporate a treatment technology for remediation of explosives. The treatment media would need to be tested and would likely include carbon, iron, palladized iron, biological, or possibly peat alone or in some combination. Extensive bench and pilot scale work would be necessary prior to implementing this technology at MMR. No commercial vendors are available for this technology in an aquifer containing explosive contaminants.

2.3.4 In-Situ Chemical Oxidation

In-situ chemical oxidation consists of the introduction of chemical oxidizers into the aquifer to destroy organic contaminants. Typically, this technology involves the installation of well(s) whereby the oxidizer is introduced into the aquifer through the well. The oxidizer is usually used to treat a hot spot rather than a large dilute contaminant plume, due to the costs of treatment. Typical oxidizers used in groundwater treatment include ozone, hydrogen peroxide, dichromate, and potassium permanganate. The use of ozone and hydrogen peroxide in combination is called peroxone. It was reported that peroxone has been tested in a treatability study to remove TNT (Zappi, 1998). One drawback of using peroxone is the oxidizer is nonselective oxidizing contaminants as well as carbonates and bicarbonates. The more carbonate present in the groundwater the more oxidizer needed to treat a given mass of contaminants, since some oxidizer will react with the carbonate and thus not be available for contaminant destruction. Given the low alkalinity of groundwater at MMR this should not be a major issue. Although the treatment method has not been tested on RDX or HMX, based on the chemistry of these compounds they should be susceptible to chemical oxidation. The approach is fairly new and only a few environmental engineering firms have the expertise for this technology. Extensive bench and pilot-scale work would be necessary prior to implementing this technology at MMR.

2.3.5 Monitored Natural Attenuation

Monitored Natural Attenuation (MNA) consists of the reduction of contaminant mass through non-engineered activities. The principal reliance is upon destruction of the contaminant through natural, non-engineered biological or oxidation-reduction processes. This approach has been demonstrated for TNT, which is known to degrade (Balasco, 1996).

The only Record of Decision (ROD) utilizing MNA for explosives is at the Sierra Army Depot in Herlong, California (Balasco et al. 1996). In this case, the principal explosive contaminant was TNT. The selection of MNA at this site was based on the following; negligible horizontal and

vertical plume movement, no current or future receptors, limitations of pump-and-treat, cost, reevaluation of site-specific data, and ongoing routine monitoring. A feasibility study of MNA was conducted at the Joliet AAP and found evidence to support a MNA remediation approach for TNT, RDX, and TNB at this site (Pennington et al. 1998). The study found all three compounds were being attenuated and therefore MNA could be considered as an alternative for this site. Implementing a MNA approach at MMR would require collection of additional geochemical data to assess the rate and process of biological reduction of TNT. Ground water modeling would also be necessary to estimate travel times to receptors and predicted maximum concentrations at the compliance point. Modeling would have to be performed to determine the effect of dilution and dispersion on the RDX and HMX contaminant mass to see if this is a viable option, given the distance to the MMR property boundary. The approach is fairly new and only a few environmental engineering firms have the expertise for this technology.

3.0 SOIL REMEDIAL TECHNOLOGIES

A comparison of ex-situ and in-situ soil remedial technologies that passed the initial screening in Section 1.1 based on effectiveness, implementability, and cost is presented in Tables 3a and 3b. The seven criteria used to evaluate the three elements are discussed in Section 2. Each soil remedial technology is discussed in detail in the following sections. Ogden is not recommending a technology for soil treatment until the volume, distribution, and concentration of soil contamination has been determined. Sampling is planned within the next few months to determine this distribution. Once these data are available, they may be applied to model the soil contamination concentration protective of groundwater. The recommended alternative for soil remediation is dependent upon the depth and distribution of contaminants and the soil cleanup target. In addition, the determination of the compliance with soil ARARs for each technology is unclear until soil cleanup levels are established for the site.

3.1 No-Action

The No Action alternative provides a baseline to which other alternatives are compared. Under this alternative, no action would be taken to implement remedial activities to control migration of COCs away from the Demolition 1 Area.

3.2 Excavation and Disposal or Treatment

There are at least six variations under the excavation alternative. One alternative is the off-site disposal of contaminants at a landfill. The other five scenarios involve on-site treatment such as Composting, Biotreatment, White Rot Fungus, Incineration, or Thermal Desorption. The depth of soil needing to be removed largely controls the feasibility and excavation costs. If the contamination is limited to the surface soil, excavation can be a relatively low-cost remedial alternative. Excavation can require extensive soil management and site restoration. Most large-scale environmental engineering firms have experience with this technology.

Final Evaluation of Remedies for Demo 1

Table 3a. Comparison of Ex-Situ Soil Remedial Technologies.

Criteria	Ex-Situ Soil Remedial Technologies		
	Off-Site Landfill Disposal	Composting	Biotreatment
Overall Protection of Human Health and the Environment	Protective of human health and the environment.	Protective of human health and the environment.	Protective of human health and the environment.
Compliance with ARARs	Would comply with ARAR's.	Would comply with ARAR's.	Would comply with ARAR's.
Long-term Effectiveness and Performance	An acceptable level of risk would remain	An acceptable level of risk would remain	An acceptable level of risk would remain.
Reduction of Toxicity, Mobility, or Volume through Treatment	Does not reduce toxicity or volume of contaminants.	Reduction of toxicity, mobility, and volume through on-site treatment to remove explosives from soil.	Reduction of toxicity, mobility, and volume through on-site treatment to remove explosives from soil.
Short-term Effectiveness	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.
Implementability	Materials and services available.	Materials and services available.	Materials and services available.
Cost	Medium to high	Medium	Medium to high
Recommendation	Recommended as a viable treatment option.	Recommended as a viable treatment option.	Recommended as a viable treatment option.

Final Evaluation of Remedies for Demo 1

Table 3a. Comparison of Ex-Situ Soil Remedial Technologies (continued).

Criteria	Ex-Situ Soil Remedial Technologies		
	White Rot Fungus	Incineration	Low Temp Thermal Desorption
Overall Protection of Human Health and the Environment	Protective of human health and the environment.	Protective of human health and the environment.	Protective of human health and the environment.
Compliance with ARARs	Would comply with ARAR's.	Would comply with ARAR's.	Would comply with ARAR's.
Long-term Effectiveness and Performance	The technology has not been demonstrated for explosives other than TNT so the performance is unknown. It is anticipated the long-term effectiveness would result in an acceptable level of risk.	An acceptable level of risk would remain	An acceptable level of risk would remain
Reduction of Toxicity, Mobility, or Volume through Treatment	Reduction of toxicity, mobility, and volume through on-site treatment to remove explosives from soil.	Reduction of toxicity, mobility, and volume through on-site treatment to remove explosives from soil.	Reduction of toxicity, mobility, and volume through on-site treatment to remove explosives from soil.
Short-term Effectiveness	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.
Implementability	Innovative technology may be feasible. Materials and services limited.	Materials and services available.	Materials and services available.
Cost	Medium to high	High	Medium to high
Recommendation	Recommended as a viable treatment option.	Recommended as a viable treatment option.	Recommended as a viable treatment option.

Final Evaluation of Remedies for Demo 1

Table 3b. Comparison of In-Situ Soil Remedial Technologies.

Criteria	In-Situ Soil Remedial Technologies		
		Landfarming	In-Situ Vitrification
Overall Protection of Human Health and the Environment		Protective of human health and the environment.	Protective of human health and the environment.
Compliance with ARARs		Would comply with ARAR's.	Would comply with ARAR's.
Long-term Effectiveness and Performance		An acceptable level of risk would remain	An acceptable level of risk would remain.
Reduction of Toxicity, Mobility, or Volume through Treatment		Reduction of toxicity, mobility, and volume through on-site treatment to remove explosives from soil.	Reduction of toxicity, mobility, and volume through on-site treatment to remove explosives from soil.
Short-term Effectiveness		No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.
Implementability		Materials and services available.	Innovative technology could be implemented. Materials and services limited.
Cost		Medium to high.	High
Recommendation		Recommended as a viable treatment option if contamination is limited to surface soil, i.e not greater than 2 ft.	Not recommended as a viable treatment option.

Final Evaluation of Remedies for Demo 1

Table 3b. Comparison of In-Situ Soil Remedial Technologies (continued).

Criteria	In-Situ Soil Remedial Technologies		
	Thermal Blanket	Electrokinetics	Deep Soil Mixing
Overall Protection of Human Health and the Environment	Protective of human health and the environment.	Protective of human health and the environment.	Protective of human health and the environment.
Compliance with ARARs	Would comply with ARAR's.	Would comply with ARAR's.	Would comply with ARAR's.
Long-term Effectiveness and Performance	The technology has not been demonstrated for explosives so the performance is unknown. It is anticipated the long-term effectiveness would result in an acceptable level of risk.	The technology has not been demonstrated for explosives so the performance is unknown. It is anticipated the long-term effectiveness would result in an acceptable level of risk.	The technology has not been demonstrated for explosives so the performance is unknown. It is anticipated the long-term effectiveness would result in an acceptable level of risk.
Reduction of Toxicity, Mobility, or Volume through Treatment	Reduction of toxicity, mobility, and volume through in-situ treatment to remove explosives from soil.	Reduction of toxicity, mobility, and volume through in-situ treatment to remove explosives from soil.	Reduction of toxicity, mobility, and volume through in-situ treatment to remove explosives from soil.
Short-term Effectiveness	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.
Implementability	Innovative technology could be implemented. Materials and services limited.	Innovative technology could be implemented. Materials and services limited.	Innovative technology could be implemented. Materials and services limited.
Cost	Medium	Medium to high.	Medium to high.
Recommendation	Recommended as a viable treatment option if contamination is not greater than 2 ft.	Recommended as a viable treatment option if contamination is not greater than 60 ft.	Recommended as a viable treatment option if contamination is not greater than 40 ft.

Final Evaluation of Remedies for Demo 1

Table 3b. Comparison of In-Situ Soil Remedial Technologies (continued).

Criteria	In-Situ Soil Remedial Technologies		
	Jet Grouting	Soil Flushing	Phytoremediation
Overall Protection of Human Health and the Environment	Protective of human health and the environment.	Protective of human health and the environment.	Protective of human health and the environment.
Compliance with ARARs	Would comply with ARAR's.	Would comply with ARAR's.	Would comply with ARAR's.
Long-term Effectiveness and Performance	The technology has not been demonstrated for explosives so the performance is unknown. It is anticipated the long-term effectiveness would result in an acceptable level of risk.	The technology has not been demonstrated for explosives so the performance is unknown. It is anticipated the long-term effectiveness would result in an acceptable level of risk.	The technology has not been demonstrated for explosives so the performance is unknown. It is anticipated the long-term effectiveness would result in an acceptable level of risk.
Reduction of Toxicity, Mobility, or Volume through Treatment	Reduction of mobility through on-site treatment to isolate explosives soil. No change in toxicity or volume of contaminants	Reduction of toxicity, mobility, and volume through in-situ treatment to remove explosives from soil.	Reduction of toxicity, mobility, and volume through in-situ treatment to remove explosives from soil.
Short-term Effectiveness	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.
Implementability	Innovative technology could be implemented. Materials and services limited.	Innovative technology could be implemented. Materials and services limited.	Innovative technology could be implemented. Materials and services limited.
Cost	Medium	Medium	Low
Recommendation	Not recommended as a viable treatment option.	Recommended as a viable treatment option.	Recommended as a viable treatment option if contamination is limited to surface soil, i.e not greater than 2 ft.

Final Evaluation of Remedies for Demo 1

Table 3b. Comparison of In-Situ Soil Remedial Technologies (continued).

Criteria	In-Situ Soil Remedial Technologies	
	No-Action	Capping
Overall Protection of Human Health and the Environment	Not protective of human health and the environment.	Protective of human health and the environment.
Compliance with ARARs	Would not comply with ARAR's.	Would comply with ARAR's.
Long-term Effectiveness and Performance	An unacceptable level of risk would remain.	An unacceptable level of risk would not remain.
Reduction of Toxicity, Mobility, or Volume through Treatment	No reduction in toxicity, mobility or volume.	Reduction of mobility through on-site treatment to isolate explosives soil. No change in toxicity or volume of contaminants
Short-term Effectiveness	No increased risk to the surrounding community or the environment.	No increased risk to the surrounding community or the environment. Minimal risk to workers during remedial action and no environmental impacts identified.
Implementability	Materials and services available.	Innovative technology could be implemented. Materials and services limited.
Cost	None	Low to Medium.
Recommendation	Not recommended as a viable treatment option.	Not recommended as a viable treatment option.

3.2.1 Excavation and Landfill Disposal

3.2.1.1 On Site Landfill Disposal

Excavation with on-site disposal consists of excavation of the contaminated soil and transport on-site to a landfill. However, the existing on-site disposal facility at MMR, LF-1, has been closed. There is no other open on-site disposal facility at MMR and therefore this technology is not listed in Table 3a.

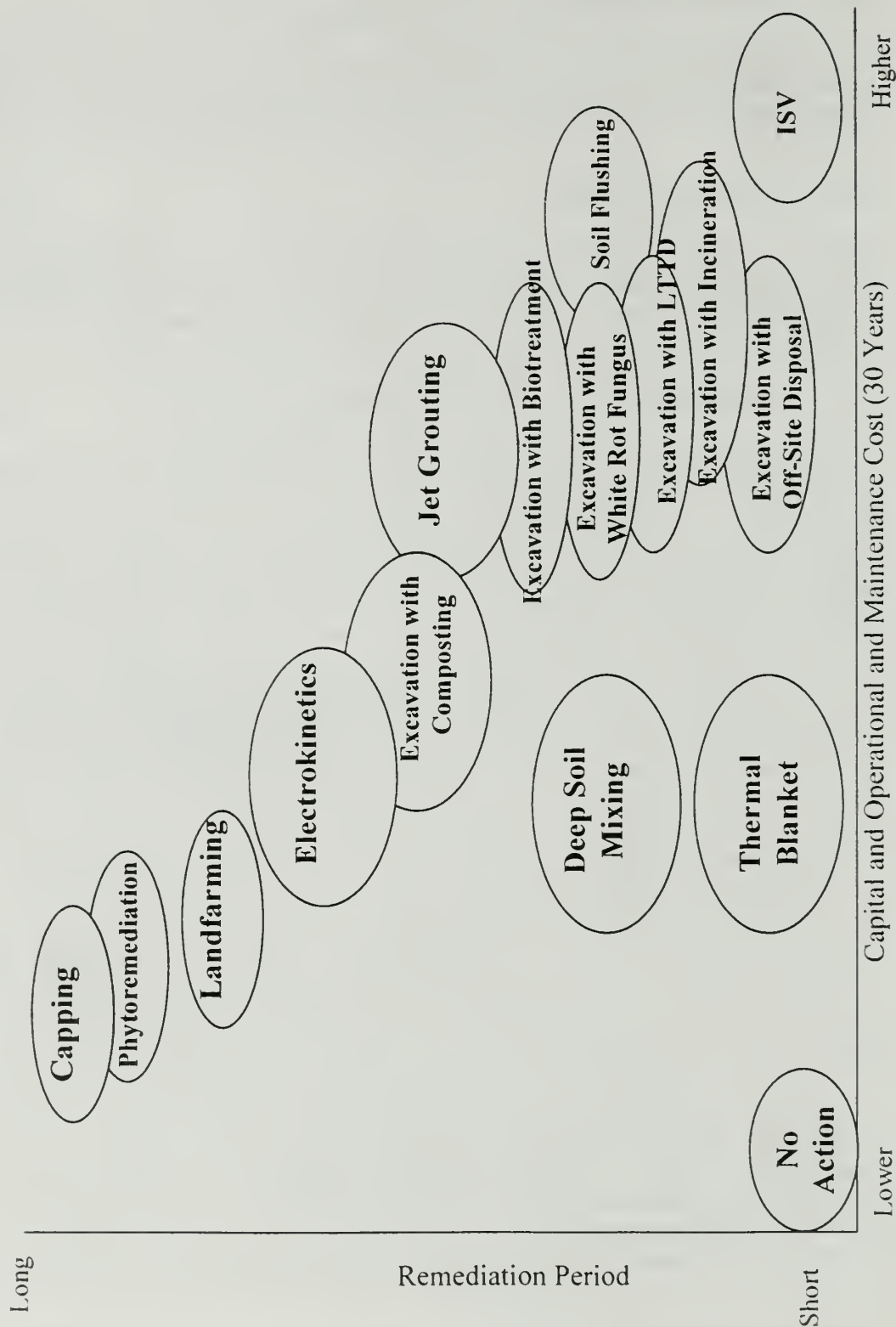
3.2.1.2 Off Site Landfill Disposal

Excavation with off-site disposal consists of excavation of the contaminated soil and transport off-site to a landfill disposal site. This is proven technology but disposal costs are high if the soil is deemed a hazardous waste. Figure 4 presents a comparison of the relative cost and performance of excavation with off-site disposal, as well as other soil treatment technologies.

3.2.2 Excavation and Treatment with Composting

Excavation and treatment with composting consists of excavation of the soil and placement into bio-piles. There are four composting methods; static-pile, in-vessel static-pile, mechanically agitated in-vessel, and windrow. In static-pile composting the excavated soil is placed in a pile under a protective shelter and mixed with a readily degradable carbon source. The pile is aerated to maintain aerobic and thermophilic conditions using forced air. Bulking agents such as sawdust, straw, bark, and wood chips, and organic amendments such as animal manure or vegetable processing waste are sometimes added. In-vessel static-pile composting is similar to static pile composting except the bio-pile is placed in a closed vessel. In a mechanically agitated in-vessel composting system, excavated soil is aerated and mixed with a carbon source in a mechanical composter. Windrow composting is similar to static-pile composting, except the compost is aerated mechanically rather than forced air. The composting process has been proven for TNT, DNT, RDX, HMX, and tetryl and is a well accepted method for explosives treatment of soil (EPA, 1998b; Preston, 1998; Craig and Sisk, 1994). Composting has been in use for over 15 years for the treatment of explosive contaminated soils. Drawbacks to the technology include; a 30 percent increase in treatment volume due to the use of bulking agents, a requirement for a large surface area in terms of managing the bio-piles, and long treatment times (months, especially in cold climates) (EPA, 1998b; Preston, 1998; Craig and Sisk, 1994). The advantages of composting include the binding of degradation products to humic material and general low cost as compared to other technologies. Treatability studies would be necessary to identify local materials that could be used for amendments for composting. Recent work at the Iowa AAP suggests that a mixture of pig manure (40%), cornstalk (40%), and soil (20%) was successful in remediating RDX, HMX, and TNT (Preston et al. 1998). TNT concentration reductions were 47%, HMX 77%, and RDX 98.7%. The initial starting explosive levels were in the 100's mg/kg. In comparison, the current maximum concentration of explosives in soil at Demolition 1 is 3.9 mg/kg of RDX. The study at the Iowa AAP evaluated mixtures of local materials due to the cost of using sawdust. Studies were also performed at the Louisiana AAP which found windrow composting to be the most cost effective composting method (EPA, 1993). Treatability studies have also been conducted at the Umatilla Army Depot in Hermiston, Oregon and the U. S. Naval Submarine Base in Bangor, Washington (Craig and Sisk, 1994). Both treatability tests were

Figure 4. Cost comparison of various soil remedial technologies identified for Demolition Area 1 at MMR.



Final Evaluation of Remedies for Demo 1

successful and the composting technology was selected as the remedy of choice in the ROD for both sites. Estimates of treatment costs for composting have ranged from \$206 to \$766/ton (Craig et al. 1997). Most large-scale environmental engineering firms have experience with this technology.

3.2.3 Excavation and Biotreatment

The technology consists of excavation of the soil, addition of water and nutrients, and placement in an ex-situ bioreactor, which can either be a closed vessel or lagoon. The technology is often referred to as bioslurry. This technology allows good process control but a drawback is the potential production of degradation products that are more toxic than the starting material. Although these same degradation products are formed during composting they become bound with the humic material and become non-bioavailable. A full-scale test of this process has been conducted at the Joliet AAP (EPA, 1993) and at the Weldon Spring Ordnance Works site (Simplot, 1998). The Joliet AAP study used an aerobic bioslurry which resulted in 99 percent removal of TNT, HMX, and RDX. TNT removal rates at the Weldon Spring Ordnance Works site using the SABREO process were 99.4 percent (Simplot, 1998). The initial TNT levels were in the 10-100 ppm range. An anaerobic bioslurry test is being conducted at the Iowa AAP. Drawbacks to the bioslurry system are the high capital and operational and maintenance costs as compared to composting, landfarming, or treatment with White Rot Fungus (Craig et al. 1997). Most large-scale environmental engineering firms will have experience with this technology.

3.2.4 Excavation and Treatment with White Rot Fungus

The technology consists of excavation of the soil and placement in a pile. White Rot Fungus is then mixed with soil, nutrients, and bulking agents. Degradation of TNT with White Rot Fungus has been reported (Fernando et al. 1990 and Berry and Boyd, 1985). A pilot scale test was conducted at the Naval Submarine Base in Bangor, Washington and resulted in a 41 percent reduction of TNT levels. No reference was found for the application of the technology to the contaminants RDX, HMX, or DNT. Although the approach has been around for about ten years its application has been limited and as a consequence only a few environmental engineering firms have the expertise for this technology. Extensive bench and pilot scale work would be necessary prior to implementing this technology at MMR.

3.2.5 Excavation and Treatment with Incineration

This technology involves excavation of the soil and then incineration either on-site or off-site. Three types of incineration devices have been used by the Army and include; rotary kiln incinerator, deactivation furnace, and contaminated waste processor. Rotary kiln incineration has been employed at the Cornhusker AAP, Louisiana AAP, Savanna Army Depot, and Alabama AAP. The explosive contaminants incinerated includes RDX, TNT, HMX, 1,2,3-TNB, 1,3-DNB, 2,4-DNT, 2,6-DNT, 2A-4,6-DNT, and tetryl. The explosive detection limits of analyzed treated soil at those sites was (1-2 ppm), which is higher than the explosive soil concentrations seen at MMR. The excavation trigger criteria for all four sites are higher than the concentrations of explosives observed at MMR. Incineration tends to be one of the more costly remedial alternatives and least publicly favorable due to concerns about air emissions. However, incineration is a demonstrated technology that is highly effective. Most large-scale environmental engineering firms have experience with this technology.

Final Evaluation of Remedies for Demo 1



3.2.6 Excavation and Treatment with Low Temperature Thermal Desorption

Low Temperature Thermal Desorption (LTTD) consists of excavation of soil and then treatment with heat. The off-gases are then combusted in a flame oxidation unit or otherwise treated. Laboratory tests by the Army showed this technology would work for RDX, HMX, and TNT. However, the TNT degradation products, 3,5-dinitroaniline and 3,5-dinitrophenol, which were produced in the process, were found to be recalcitrant and may be toxic. This technology would only be appropriate for those sites at MMR that do not contain TNT in the soil. Data collected from the Phase I IAGS at MMR indicated the absence of TNT from soil in the Demolition Area 1. Most large-scale environmental engineering firms have experience with this technology.

3.3 In Situ Treatment

3.3.1 Landfarming

Landfarming consists of placing the soil in lined treatment plots of 12 to 18 inches deep that are then rototilled to mix nutrients, moisture and bacteria. The difference between landfarming and composting is the soil is not transported far from its source, it is not enclosed in a building, and a carbon source is not generally added. Landfarming is relatively inexpensive and simple to implement as compared to other biotechnologies. One drawback to landfarming is the large area needed for treatment. It is unclear if landfarming is applicable to soils containing explosives. Most large-scale environmental engineering firms have experience with this technology.

3.3.2 In-Situ Vitrification

In situ vitrification (ISV) consists of heating the soil to a sufficient temperature so that it is turned into glass rendering the contaminants immobile. Electrical current is transmitted to an electrode in the ground, which generates heat sufficient to melt the soil. A hood with negative pressure is placed over the electrodes to collect any off-gases. The technology works best in unsaturated soils. The unsaturated zone at Demolition Area 1 is over 50 ft. No information could be found on its use for explosives. However, this technology should be applicable as long as the percent level of explosives in soil is less than 10 percent. Soils with greater than 10 percent explosives are an explosive hazard. Due to the high power requirements the technology is costly to implement, although the remediation time is measured in weeks rather than years. Geosafe is the only commercial vendor for this technology. Extensive bench and pilot scale work would be necessary prior to implementing this technology at MMR.

3.3.3 Thermal Blanket

The technology consists of using heat to destroy contaminants present in the shallow surface soil, less than 18 inches deep, in a similar manner to thermal desorption. The system consists of a series of coils placed on the ground surface that generate heat. The coils are insulated above with a layer of vermiculite and have a vapor extraction system under negative pressure to capture any off-gases. The off-gases are treated in a thermal oxidizer. This technology has been used successfully on a PCB and dioxin contaminated site. Contaminant reduction efficiencies were 99.99 percent. The technology has not been used for surface soils contaminated with explosives but appears to be amenable for these compounds. The remediation time-period is measured in

weeks. The one drawback is the large amount of electricity required, however the vendor uses a trailer mounted diesel generator. The technology is marketed by Shell Oil Company. Extensive bench and pilot scale work would be necessary prior to implementing this technology at MMR.

3.3.4 Electrokinetics

Electrokinetics consists of placing vertical electrodes and treatment zones in the subsurface. The electrodes and treatment zones are installed using a large vibratory hammer, although lower cost technologies are being evaluated for installation activities, such as jet grouting and pneumatic fracturing. The maximum viable depth is less than 100 ft below ground surface and the technology is applicable to both saturated and unsaturated zone soils. An electrical current is established between the anode and cathode. The negatively charged ions such as chloride are drawn to the cathode. Since the chloride is dissolved in water the water molecule is also dragged towards the cathode. If a contaminant is dissolved in the water, such as an explosive it is also dragged towards the cathode along with the water. The treatment zones are installed perpendicular to the electrokinetic induced gradient. As the contaminated water is driven through the treatment zone it is remediated. The remediation system is designed such that the residence time of the contaminant in the treatment zone results in complete remediation. A series of cells are installed to cover the contaminated media. Remediation time is in the two to five year time frame depending on the desired time for remediation, which is a function of the energy expenditure. The treatment options include iron, palladized iron, carbon, or biological treatment cells. The one drawback to the technology is the large amount of electricity used and the required electrical infrastructure. Although not demonstrated for explosives the compounds of interest are ideally suited for this technology. The only commercial vendors are Electrokinetics and Monsanto although neither has applied their technologies to explosives. Extensive bench and pilot scale work would be necessary prior to implementing this technology at MMR.

3.3.5 Deep Soil Mixing

Deep soil mixing consists of using augers to mechanically mix soil in-situ. Various treatments are then mixed with the soil to facilitate destruction of the contaminants. The potential treatment amendments, iron, potassium permanganate, or biological organisms would need to be evaluated for explosives. The technology is limited to a depth of approximately 40-ft below ground surface. A shroud encloses the augers to capture any off-gases, which are then destroyed with a thermal oxidizer. Although the technology has been demonstrated for VOCs it has not been applied to a site with explosive contaminated soils. The technology would not be cost-effective for treating a site with only surface soil contamination, i.e. less than 2 feet or a very large site, i.e. more than 1 acre. The approach is fairly new and only a few environmental engineering firms have the expertise for this technology. Extensive bench and pilot scale work would be necessary prior to implementing this technology at MMR.

3.3.6 Jet Grouting

The technology consists of using an in-situ jet to mix a grout with the subsurface soil. The grout can consist of cement, bentonite, bentonite cement, or various polymers. The process decreases the permeability of the soil, which results in a decrease in infiltration of precipitation through the contaminated soil. The technology would not be applicable to surface soil contamination. The approach has been around at least since the 1970s in the geotechnical industry however its application to the environmental industry is fairly new and only a few environmental engineering

firms have the expertise for this technology. Extensive bench and pilot scale work would be necessary prior to implementing this technology at MMR.

3.3.7 Soil Flushing

Involves the introduction of a solvent or surfactant to solubilize and mobilize the contaminants. Soil flushing can be done in an ex-situ or in-situ mode, although most remedial actions to date have been in the ex-situ mode. Studies by Kaplan and Kaplan (1982) found that amino surfactants can precipitate TNT into an insoluble precipitate. The surfactant in this case immobilizes the TNT in the soil. However, the quantity of surfactant necessary for treatment was not cost effective.

Another possibility is to use extracted groundwater as the flushing agent (solvent) to accelerate the dissolution of explosive particulates in or on the soil and movement of the contaminants out of the soil into the groundwater. The contaminants would then be captured in a downgradient extraction well to capture and treat the contaminants. The water would be pumped to the surface, treated, and then the treated water would be sprayed over the soil. Extensive bench and pilot scale work would be necessary prior to implementing this technology at MMR as well as modeling to design a system to maintain hydraulic control. Most large-scale environmental engineering firms have experience with this technology.

3.3.8 Phytoremediation

Phytoremediation consists of using plants to uptake and either transform the contaminant to a non-toxic compound or immobilize it as a non-bioavailable compound. Typically, the technology is limited to explosives within the root depth of the plant, in most cases this is 1-2 feet. The technology applies to shallow soils as well as sediments in shallow water, less than 2 ft of water. Studies by Medina et al (1998) found the technology suitable for TNT although some amino-DNT, trinitrobenzene, and dinitroaniline accumulation was observed and could prove problematic. Dinitroaniline may be a toxic compound. Pilot-scale phytoremediation experiments have been conducted at the Volunteer AAP, Iowa AAP, and Milan AAP. The study at the Milan AAP found all plant species to enhance the removal of TNT from shallow groundwater. Phytoremediation of RDX and HMX was less successful but may be the result of problems in analysis (Best et al. 1997). The study at the Iowa AAP found negligible removal of TNT and RDX by the plants in surface water, however the result suggest a plant microorganism symbiotic relationship which results in microbiological reduction of TNT and RDX (Best et al. 1997). This technology would not be applicable for groundwater at this site. Remediation of the soil is slow with this technology. The approach is fairly new and only a few environmental engineering firms have the expertise for this technology. Extensive bench and pilot scale work would be necessary prior to implementing this technology at MMR.

3.3.9 Capping

This technology consists of placing a low permeability cap (clay, asphalt, geomembrane liner, or combination) to decrease the infiltration of precipitation through the contaminated soil. This approach would require fate-and-transport modeling to assess if the reduction in infiltration is sufficient to lower the amount of contaminants reaching the aquifer. Most large-scale environmental engineering firms have experience with this technology.

4.0 CONCLUSIONS

The proven groundwater option is hydraulic containment using carbon as the treatment medium. Pilot studies would be necessary for other treatment media used with hydraulic containment. Various new treatment media such as zero-valent iron or peat might be effective. All the hydraulic containment scenarios could be combined with reinjection or a barrier wall with various combinations possible to reduce the volume of water needing to be extracted and treated. A number of innovative groundwater remediation technologies and treatment media are currently being tested at sites across the United States. Innovative technologies, which could be applied at Demolition Area 1, potentially include a reactive barrier wall or a horizontal in-situ recirculation well. Depth may be a limiting factor for the application of a reactive barrier wall at Demolition Area 1. However, these are not proven technologies for explosives and would require bench-scale and/or pilot testing to confirm feasibility.

The only demonstrated technologies for soil remediation are excavation with incineration or composting. Potential innovative soil remediation technologies include deep soil mixing, soil flushing, landfarming, phytoremediation, thermal blanket, and electrokinetics. Multiple technologies are sometimes used to create a treatment train approach to remediation. Greater remediation success has been achieved in the last several years using combinations of technologies that complement each other and this is a possibility to consider for the Demolition Area 1.

5.0 RECOMMENDATIONS

Prior to conducting feasibility or treatability studies or selection of a remedial technology for the Demolition Area 1 at MMR, soil cleanup goals must be established. Once these targets are established it will then be possible to compare the possible remedial alternatives on a cost and performance basis. Clean-up goals are needed to determine the targeted volume of soil to be remediated. These cleanup goals should be based on a fate-and-transport model with the results incorporated into risk assessment calculations to derive soil cleanup numbers protective of human health and the environment.

6.0 REFERENCES

- Agrawal, A. and P. G. Tratnyek. 1995. Reduction of nitro aromatic compounds by zero-valent iron metal. *Environmental Science and Technology*.
- Agrawal, A., P. G. Tratnyek, P. Stoffyn-Egli, and L. Liang. 1995. Processes affecting nitro reduction by iron metal: Mineralogical consequences of precipitation in aqueous carbonate environments. Paper Presented at the American Chemical Society Annual Meeting. April 2-7. Anaheim, CA.
- Agrawal A. and P. G. Tratnyek. 1994. Abiotic remediation of nitro-aromatic groundwater contaminants by zero-valent iron. Paper Presented at the American Chemical Society, March 13-18. San Diego, CA.
- Balasco, A. A., R. C. Bowen, K. R. Cahill, and J. L. Mahannah. 1996. Review of the Utility of Natural Attenuation for Remediating Contaminated Army Sites. Contract Report IRRP-

Final Evaluation of Remedies for Demo 1

- 96-1. Prepared by Arthur D. Little, Inc. Cambridge, MA for the U. S. Army Corp of Engineers, Waterways Experiment Station. Vicksburg, MS.
- Berry, D. F. and S. A. Boyd. 1985. Decontamination of soil through enhanced formation of bound residues. *Environmental Science and technology*. 19:1132-1133.
- Best, E.P.H., M. E. Zappi, H. L. Fredrickson, S. L. Sprecher, S. L. Larson, and J. L. Miller. 1997. Screening of Aquatic and Wetland Plant Species for Phytoremediation of Explosives-Contaminated Groundwater from the Iowa Army Ammunition Plant. Technical Report EL-97-2. U. S. Army Corps of Engineers, Waterways Experiment Station. Vicksburg, MS.
- Best, E.P.H. and S. L. Sprecher. 1996. Phytoremediation of Explosives-Contaminated Groundwater using Constructed Wetlands, Phase I Report: Plant Screening Study-Submerged Plant Species. Draft Letter Report for Army Environmental Center, U. S. Army Corps of Engineers Waterways Experiment Station. Vicksburg, MS.
- Bradley, P. M., and F. H. Chapelle. 1995. Factors affecting microbial 2,4,6-trinitrotoluene mineralization in contaminated soil. *Environmental Science and Technology*. 29:802-806.
- Bradley, P. M., F. H. Chapelle, J. E. Landmeyer, and J.G. Schumacher. 1994. Microbial transformation of nitroaromatics in surface soils and aquifer materials. *Applied and Environmental Microbiology*. 60:2170-2175.
- Brannon, J. M., C. B. Price, and C. Hayes. 1998. Abiotic transformation of TNT in montmorillonite and soil suspensions under reducing conditions. *Chemosphere*. 36:1453-1462.
- Brannon, J. M., C. B. Brice, and C. Hayes. 1997. Abiotic and Biotic TNT Transformations. Technical Report IRRP-97-3. U. S. Army Corps of Engineers, Waterways Experiment Station. Vicksburg, MS.
- Bricka, R. M. and E. C. Fleming. 1995. Use of Activated Carbon for the Treatment of Explosives-Contaminated Groundwater at the Picatinny Arsenal. Technical Report EL-95-31. U. S. Army Corps of Engineers, Waterways Experiment Station. Vicksburg, MS.
- Bruns-Nagel, D., J. Breitung, E. von Low, K. Steinbach, T. Gorontzy, M. Kahl, K. H. Blotevogel, and D. Gemsa. 1996. Microbial transformation of 2,4,6-trinitrotoluene in aerobic soil columns. *Applied and Environmental Microbiology*. 62:2651-2656.
- Craig, H. D., W. E. Sisk, M. D. Nelson, and W. H. Dana. 1997. Bioremediation of explosives-contaminated soils: A status review. *Proceedings of the 10th Annual Conference on Hazardous Waste Research*. pp. 146-179.
- Craig, H. D. and W. Sisk. 1994. The composting alternative to incineration of explosives contaminated soil, in *Tech Trends*. EPA-542-N-94-008. U. S. Environmental Protection Agency.

Final Evaluation of Remedies for Demo 1

- DOE. 1998. Solar detoxification of explosives in water. <http://es.epa.gov/new/funding/serdp/fy93cm12.html>. U. S. Department of Energy.
- EPA. 1998a. Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Groundwater. EPA/600/R-98/128. U. S. Environmental Protection Agency. Washington, DC.
- EPA. 1998b. Bioreactors and soil mixing system at a TNT-contaminated site in Bangor, Washington. <http://www.nttc.edu/env/site95/demo/complete/simplot.html>. U. S. Environmental Protection Agency.
- EPA. 1998c. Common Treatment technologies for explosives in soil, sediment, and sludge. http://www.frtr.gov/matrix/section2/2_7_2.html. U. S. Environmental Protection Agency.
- EPA. 1993. Approaches for the Remediation of Federal Facility Sites Contaminated with Explosive or Radioactive Wastes. EPA/625/R-93/013. U. S. Environmental Protection Agency, Office of Research and Development. Cincinnati, OH.
- EPA. 1992. Evaluation of Ground-Water Extraction remedies: Phase II, Volume I –Summary Report. Publication 9355.4-05. U. S. Environmental Protection Agency, Office of Emergency and Remedial Response. Washington, DC.
- Fernando, T., J. A. Bumpus, and S. D. Aust. 1990. Biodegradation of TNT (2,4,6-trinitrotoluene) by *Phanerochaete chrysosporium*. Applied Environmental Microbiology. 56:1667-1671.
- Fleming, E. C., R. Cerar, and K. Christenson. 1996. Removal of RDX, TNB, TNT, and HMX from Cornhusker Army Ammunition Plant Waters Using Adsorption Technologies. Technical Report EL-96-5. U. S. Army Corps of Engineers, Waterways Experiment Station. Vicksburg, MS.
- Fleming, E. C., R. M. Bricka, S. R. Bailey. 1995. Ultraviolet/Chemical Oxidation Treatment of RDX-Contaminated Waters at Picatinny Arsenal. Technical Report EL-95-7. U. S. Army Corps of Engineers, Waterways Experiment Station. Vicksburg, MS.
- Haigler, B. E. and J. C. Spain. 1996. Degradation of nitroaromatic compounds by microbes. Environmental Science and Technology. 46:59-68.
- Heilmann, H. M., U. Wiesmann, and M. K. Stenstrom. 1996. Kinetics of the alkaline hydrolysis of high explosives RDX and HMX in aqueous solution and adsorbed to activated carbon. Environmental Science and Technology. 30:1485-1492.
- Hinshaw, G. D., C. B. Fanska, D. E. Fiscus, and S. A. Sorensen. 1987. Granular Activated Carbon (GAC) System Performance Capabilities and Optimization. AMXTH-TE-CR87111. Report for U. S. Army Toxic and Hazardous Materials Agency. Aberdeen Proving Ground, MD. Midwest Research Institute. Kansas City, MO.

Final Evaluation of Remedies for Demo 1

- Horney, D. P., P. D. Mackenzie, J. J. Salvo, and T. M. Sivavec. 1995. Zero-Valent Iron Treatability Study for Groundwater Contaminated with Chlorinated Organic Solvents at the Paducah, KY GDP Site. Prepared by GE Corporate Research and Development, Schenectady, NY for the U. S. Department of Energy.
- Kaplan, D. 1995. Biotechnology and Bioremediation for Organic Energetic Compounds. Research Paper 95-41407-0-3. U. S. Army Natick Research, Development and Engineering Center. Natick, MA.
- Kaplan, D. L. and A. M. Kaplan. 1982. 2,4,6-Trinitrotoluene – Surfactant Complexes, Biodegradability, Mutagenicity, and Soil Leaching Studies. Technical Report NATICK/TR-82/006. U. S. Army Natick Research & Development Laboratories. Natick, MA.
- Kaplan, D. L. and A. M. Kaplan. 1982. 2,4,6-Trinitrotoluene – surfactant complexes: Decomposition, mutagenicity, and soil leaching studies. Environmental Science and Technology. 16:566-571.
- Knezovich, J. P., J. I. Daniels, M. K. Stenstrom, and H. M. Heilman. 1994. Chemical and Biological Systems for Regenerating Activated Carbon Contaminated with High Explosives. UCRL-JC-115974. Lawrence Livermore National Laboratory. Lawrence Livermore, CA.
- Korte, N. E. 1998. Personal communication on 7/29/98. Oak Ridge National Laboratory/Grand Junction. Grand Junction, CO.
- Korte, N. E., M. Muck, P. Kearl, R. Siegrist, T. Houk, R. Schlosser, and J. Zutman. 1998. Field Evaluation of a Horizontal Well Recirculation System for Groundwater Treatment: Field Demonstration at X-701B Portsmouth Gaseous Diffusion Plant, Piketon, Ohio. ORNL/TM-13259. Oak Ridge National Laboratory. Oak Ridge, TN.
- LeFaivre, M. H. and G. H. Peyton. 1994. Identification of Reaction By-products from Oxidative and Photolytic Remediation of Groundwater Contaminated with TNT and RDX. TM-2028-ENV (CR). Naval Facilities Engineering Services Center. Port Hueneme, CA.
- Masterson, J. P., D. A. Walter, and D. R. Leblanc. 1999. Delineation of Contributing Areas to Selected Public-Supply Wells, Western Cape Cod, Massachusetts. U. S. Geological Survey. Water-Resources Investigations Report 98-4237. Marlborough, MA.
- Masterson, J. P., D. A. Walter, and J. Savoie. 1996. Use of Particle Tracking to Improve Numerical Model Calibration and to Analyze Groundwater Flow and Contaminant Migration, Massachusetts Military Reservation, Western Cape Cod, Massachusetts. U. S. Geological Survey. Open File Report 96-214. Marlborough, MA.
- McGrath, C. J. 1998. Personal communication on 10/12/98. U. S. Army Corps of Engineers, Waterways Experiment Station. Vicksburg, MS.
- NRC. 1994. Alternatives for Ground Water Cleanup. National Research Council. National Academy Press. Washington, DC.

Final Evaluation of Remedies for Demo 1

- Nyer, E. K., D. F. Kidd, P. L. Palmer, T. L. Crossman, S. Fam, F. J. Johns, G. Boettcher, S. S. Suthersan. 1996. *In Situ Treatment Technology*. Lewis Publishers. New York, NY.
- Ogden. 1998. Draft Completion of Work Report for the Camp Edwards Impact Area Groundwater Quality Study Massachusetts Military Reservation Cape Cod, Massachusetts. July, 1998. Ogden Environmental and Energy Services. Westford, MA.
- Ogden. 1997. Draft Report in Fate and Transport of Munitions-Related Materials for the Camp Edwards Impact Area Groundwater Quality Study Massachusetts Military Reservation Cape Cod, Massachusetts. August 1997. Ogden Environmental and Energy Services, Inc. Westford, Massachusetts.
- Preston, K. T., R. Wade, K. S. Ro, S. Seiden, and M. Bergess. 1998. Bench-Scale Investigation of Composting for Remediation of Explosives Contaminated Soils from Iowa Army Ammunition Plant, Middeltown, Iowa. EL-98-7. U. S. Army Corps of Engineers, Waterways Experiment Station. Vicksburg, MS.
- Schwarzenbach, R. P., C. G. Heijman, and C. Holliger. 1994. Reduction of nitroaromatic compounds in iron and sulfate reducing environments. Preprints of Papers 207th American Chemical Society National Meeting. San Diego, CA.
- Simplot, J. R. 1998. Bioreactors and soil mixing systems at a TNT-contaminated site in Bangor, Washington. J. R. Simplot Company. Pocatello, ID.
<http://www.nttc.edu/env/site95/demo/complete/simplot.html>.
- Soli, G. 1973. Microbial Degradation of Cyclonite (RDX). NWC TP 5525. Naval Weapons Center. China Lake, CA.
- Tyndall, R. L. and A. Vass. 1995. Methods of Degrading Napalm B. U. S. Patent 5,449,618. Army Corps of Engineers. 1993. Archives Search Report, Fort Ord, CA, St. Louis District. December, 1993.
- Unkefer, P. J., M. A. Alvarez, J. L. Hanners, C. J. Unkefer, M. Stenger, and E. A. Margiotta. 1990. Bioremediation of Explosives. LA-UR-90-1930. Los Alamos National Laboratory. Los Alamos, NM.
- Zappi, M. E., E. C. Fleming, T. Miller, F. Ragan, R. Swindle, R. Morgan, S. Harvey. 1998. A Pilot-Scale Assessment of Peroxone Oxidation for Potential Treatment of Three Contaminated Groundwaters at the Rocky Mountain Arsenal, Commerce City, Colorado. Technical Report SERDP-98-7. U. S. Army Corps of Engineers, Waterways Experiment Station. Vicksburg, MS.

APPENDIX A: Estimated Pumping Rates and Drawdown

Hand-calculations on pumping rates and associated capture zones for a single pumping well were evaluated for the Demolition Area 1. These calculations were performed to assess the size of a capture zone at a given pumping rate and the amount of drawdown expected. Drawdown based on water level measurements is typically used to assess and monitor the performance of a pump-and-treat system. Two or more pumping wells would result in a larger capture zone and drawdown at lower pumping rates than a single well. However, only a single pumping well was evaluated to approximate the likely capture zone width and associated drawdown. The relationship between pumping rates and capture zone width is not likely to be linear so it is not possible to extrapolate capture zone width with the number of pumping wells. The calculations are based on conservative values reported by the USGS (Masterson et al. 1996).

The maximum width of the capture zone (W) in feet upgradient of the pumping well can be calculated using;

$$1\} \quad W = Q / h n V$$

where

Q = pumping rate (gpm)

h = thickness of unconfined aquifer, approximately 214 ft at MW-31

n = effective porosity, estimated to be 0.30, and

V = natural flow velocity, estimated to be 250 ft/yr

Using the numbers above yields the following pumping rates and associated capture zone width:

<u>Q (gpm)</u>	<u>W (ft)</u>
1	4.4
10	44
100	438
1000	4378

Modeling by the USGS shows pumping rates of 600 gpm to be sustainable and result in a minimal drawdown (Masterson et al. 1999).

The drawdown is a linear relationship and is a function of the pumping rate and velocity. A drawdown cone is the area where the groundwater table is physically depressed due to the extraction of groundwater. The capture zone is the radial area of influence and can include areas beyond the drawdown cone, i.e. water upgradient to the pumping well that that would flow into the drawdown cone.

One question important in evaluating pump-and-treat performance is whether the capture zone can be evaluated by measuring drawdown in the field. Drawdown ($h_o - h$) can be calculated using the following equations;

$$2\} \quad u = r^2 * S_y / 4Tt$$

where

Final Evaluation of Remedies for Demo 1

u = is a dimensionless number determined from a table in most hydrogeology text books

r^2 = distance from pumped well, in (ft)

S_y = specific yield which ranges from 0.01-0.30, an assumed value of 0.1 was used based on the geology at MMR,

T = transmissivity, calculated at 74,900 ft²/day based on equation 3

t = time, assumed a value of 4 years, 1460 days. Typically, it takes several years for the capture zone to reach its maximum extent.

The transmissivity (T) is calculated using the following equation;

$$3\} \quad T = Kb$$

where

K = hydraulic conductivity, assumed to be 350 ft /day based on USGS estimates

b = thickness of the aquifer (ft), assumed to be 214 ft in the area of Demo 1

The results from equation 2, in terms of u , are then looked up in a table to find $W(u)$ which is then substituted into equation 3 as follows;

$$4\} \quad h_o - h = Q/4\pi T (Wu)$$

where

$W(u)$ = value derived in a table for u

$\pi = 3.14$

Q	r^2	$h_o - h$ (ft)
10	1	0.0002
10	10	0.0001
10	100	0.0001
100	1	0.002
100	10	0.002
100	100	0.001
1000	1	0.02
1000	10	0.018
1000	100	0.013

Using these equations it is clear the drawdown cone will not be easily measured at Demolition Area 1. The accuracy of these equations is dependent upon the aquifer-input parameters, which have not been directly measured at Demolition Area 1. However, even at a pumping rate (Q) of 1,000 gpm and r^2 of 1 the drawdown (h) is only 0.02 ft. Assuming the calculations are off an order of magnitude the drawdown is still only 0.2 ft. The typical accuracy possible measuring water levels is about 0.1 ft even though it is reported to 0.01 ft. This is a typical problem in aquifer systems, which have a high flow velocity and low hydraulic gradient. Thus, it will be difficult to prove contaminant capture based solely on water level measurements. Initially, determination of the capture zone effectiveness will have to rely on groundwater modeling.

Final Evaluation of Remedies for Demo 1

Declining concentration trends in downgradient wells could be used but they sometimes are complicated by seasonal contaminant fluctuations. Another approach to evaluate pump-and-treat effectiveness is to determine the mass recovered in the extraction wells. However, the original starting mass of contaminants is usually unknown, as is the case at Demolition Area 1. Several innovative approaches to evaluating performance are dye tests or using a monitoring device such as a colloidal borescope to track colloid movement.

Final Evaluation of Remedies for Demo 1

APPENDIX B: Responses to EPA Comments dated 11/8/99 and 1/13/00 on the Draft Evaluation of Remediation Technologies for Demolition Area 1

General Comments:

1. (11/8/99) Tables 2 and 3 provide a good preliminary review of certain technologies. In the comments below, EPA addresses several of the technologies presented. However, regardless of whether EPA comments on a technology or not, EPA is not bound to any of the conclusions reached by NGB utilizing the eight comparison criteria. EPA is accepting these for working hypotheses only as NGB, EPA, and MA DEP work through the issue of which technology will best suit our needs.

The Guard agrees that the purpose of this document is to help identify which technology best suits our needs at Demo 1.

2. (11/8/99) If this document is suppose to look and read like a CERCLA "Initial Screening of Remedial Technologies" report, there are several inconsistencies and omissions from the current document. More specifically, the screening criteria should be limited to effectiveness, implementability and costs (as stated was done in the Introduction), but was not done according to the information in Tables 2 or 3. Please refer to EPA's guidance, Section 4.0, entitled "Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA, Interim Final, dated October 1998."

The Guard notes that the above document referenced by EPA is actually dated October 1988.

Sections 1-3 will be revised to clarify that the technologies discussed in Sections 2 and 3 and presented in Tables 2 and 3 are those that remain after the initial screening using effectiveness, implementability, and cost. The initial screening that resulted in these technologies was not included in this document, but can be added if necessary. Tables 2 and 3 document the detailed evaluation of the selected technologies and so contain the additional criteria.

(1/13/00) EPA requests that the initial screening of technologies be added to the document.

Information describing the initial screening of technologies has been added to Section 1.1.

3. (11/8/99) The information stated in the text, in comparison to what is provided in Tables 2 or 3, are inconsistent in several instances. This includes the summary of soil and groundwater technologies that were retained according to the Introduction, yet "not recommended" as stated in the last row of Tables 2 or 3.

Final Evaluation of Remedies for Demo 1

As indicated in the response to General Comment 2, technologies retained in the initial screening were evaluated in detail in Sections 2 and 3, as summarized in Tables 2 and 3.

4. (11/8/99) Under the groundwater technologies, a key group of groundwater options are missing. They include groundwater extraction and subsurface drains which would fall under the general category for groundwater options commonly referred to as: "groundwater collection" options. These need to be considered along with the others provided.

Groundwater extraction and reinjection wells are described under Hydraulic Containment in Section 2. Information will be added to include other groundwater collection and reinjection options in addition to wells.

Specific Comments:

1. (11/8/99) Page 2, Table 1 – Table 1 utilizes 10^{-4} cancer risk as a relevant risk level. EPA prefers that the table contain concentrations as they relate to a 10^{-6} cancer risk, and the Hazard Index of 1 for non-carcinogens. These are the "starting points" for CERCLA cleanups and most EPA regulatory programs. Please consult *Risk Assessment Guidance for Superfund, Volume 1, Part D, Section 4.1.2, "Risk-Based Remediation Goals"*.

Regulatory criteria for a 10^{-6} cancer risk are not published in EPA's drinking water regulations, EPA 822-B-96-002, therefore the 10^{-4} numbers were used. However, another column will be added to Table 1 showing a 10^{-6} risk. Table 1 is simply a compilation of the existing groundwater regulatory criteria for explosive compounds. We inadvertently left out a risk number for 2,6-DNT and this will be added to the list.

2. (11/8/99) Page 2, Section 2.0 – The paragraph on page 2 discusses current COCs based on somewhat limited sampling. Please add a paragraph discussing whether contaminants which may be encountered during more extensive sampling, such as metals, were considered in this evaluation or would be addressed otherwise.

The text will be revised as requested.

3. (11/8/99) Page 2, Section 2.0 – Under the groundwater technologies, the document does not identify in tabular format those technologies (e.g., carbon treatment, UV oxidation, etc...) that may or may not be applicable once contaminated groundwater is extracted or hydraulically contained. While the text provides a discussion of these "treatment technologies" for the groundwater, a separate technology table needs to be presented which would show the screening summary using the effectiveness, implementability and cost criteria used to screen remedial technologies.

Table 2a will be added to summarize the evaluation of ex-situ treatment options in Section 2.2. The original Table 2 (relabeled "2b") will be modified to show the

Final Evaluation of Remedies for Demo 1

evaluation of in-situ treatment options in Section 2.3.

4. (11/8/99) Page 2, Section 2.0 – Under the groundwater technologies, the document does not identify any of the remedial technologies that may or may not be viable for use once the contaminated groundwater is treated. These technologies would include, but may not be limited to, reinjection, infiltration galleries, infiltration trenches, etc.

See the response to General Comment #4.

5. (11/8/99) Page 6, Table 2 – Under the groundwater technology termed “In-Situ Recirculation Well”, it is strongly recommended that this remediation technology be retained. The Air Force has used this technology at MMR during two pilot tests and, most recently, have installed two recirculation wells in the Briarwood neighborhood of Masphe to address the axial portion of the Storm Drain 5 South (SD-5S) groundwater plume. There ARE commercially available materials and services for recirculation wells in contrast to the statement made in Table 2.

In-situ recirculation wells involve stripping of a volatile contaminant within the well and then reinjection into the aquifer. None of the explosive compounds are volatile enough for a standard In-Situ Recirculation well. It is possible that the recirculation technology could be modified with another treatment technology for remediation of explosive contaminated groundwater in-situ. However, the Guard is not aware of any stand-alone In-Situ Recirculation systems or modified systems for treating explosive contaminated groundwater. The Guard is also not aware of any commercial available In-Situ Recirculation systems designed for treating explosive compounds. This technology is considerably less proven than others for explosives, and the Guard continues to recommend that it be removed from consideration.

(1/13/00) EPA requests that information in the response to comments be incorporated in the text.

Information in the response to comments has been added to the text.

6. (11/8/99) Pages 7 and 18, Figures 3 and 4 – The two charts do not show anything with respect to No Action.

No Action will be added to these figures.

7. (11/8/99) Page 12, Section 2.3.5 – Please change the second sentence to read “The principal reliance is upon destruction of the contaminant through natural, non-engineered biological or oxidation-reduction processes”.

The text will be changed.

8. (11/8/99) Page 13, Section 3.0 – The soil treatment technologies provided in the text

Final Evaluation of Remedies for Demo 1

in sections 3.2.2 through 3.2.6 need to be presented in separate technology tables. Excavation needs to be provided as a separate soil technology. This also includes the technology for off-site disposal which is currently coupled with excavation as discussed in section 3.2.1. Also, on-site disposal should be mentioned in the soil technology section.

Table 3a will be added to summarize the evaluation of ex-situ treatment options in Section 3.2. The original Table 3 (relabeled "3b") will be modified to show the evaluation of in-situ treatment options in Section 3.3. Section 3.2.1 will be modified to discuss the excavation technology itself, with separate subsections discussing the on-site and off-site disposal options.

(1/13/00) EPA requests that on page 18 the words "surface soil" under the Recommendations should be deleted.

The text has been modified as requested.

9. (11/8/99) Page 23, Section 4.0 – The conclusions in Section 4.0 with respect to groundwater are not true, i.e., hydraulic containment of groundwater with treatment is not the only proven option. Groundwater collection through extraction and treatment should also be considered a proven option as well as in-situ recirculation wells.

Groundwater collection through extraction and treatment is the option described in this document as "hydraulic containment" (see Section 2.2). See the response to Specific Comment #4 regarding in-situ recirculation wells.

(11/8/99) Also, the reinjection statements in the conclusions need to be discussed further within the body of the text since there are various reinjection technologies that are available; all of which may or may not be applicable to Demo Area 1.

The various reinjection options will be mentioned in Section 2.0 as part of the evaluation of groundwater remedial technologies.

(1/13/00) EPA requests that the description of hydraulic containment be checked against the wording used in the CERCLA guidance.

The description of hydraulic containment in this document does not appear to be inconsistent with the CERCLA guidance.

New Specific Comment (1/13/00)

EPA indicates that on page 2 the soil concentration "3.9" should be "9.3".

Final Evaluation of Remedies for Demo 1

At the time the draft report was prepared in May 1999, the maximum concentration of 3.9 mg/kg was correct. Subsequent sample results produced a new maximum concentration of 9.3 mg/kg. The text has been updated as requested.

New Specific Comment (1/13/00)

EPA indicates that the document should be consistent with the selection of technologies that is underway for the Rapid Response Actions (RRA) that are being conducted under AO3.

The RRA technologies include excavation and biotreatment, which are discussed in general terms in Section 3.2.3. This technology is recommended as a viable treatment option in Table 3a.

JONATHAN BOURNE PUBLIC LIBRARY



0 0113 0096924 0

ADV
6903

For Reference

Not to be taken from this room

Jonathan Bourne Public Library
18 Sandwich Rd.
Bourne, MA 02532

